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The Alloy Steel Research Committee.

THE development of the Bessemer and Siemens processes of steel making during the last hundred years has made possible the heavy tonnages of steel necessary to our very mechanical civilisation ; and the advent of the electric processes has made attainable the high degree of purity demanded in many applications. But had not the metallurgist by experiment disclosed the extent to which the *properties* of steel could be modified by the addition of various special elements, many of the outstanding achievements of engineers would have been impossible. By alloying other elements with iron an amazing range of properties may be obtained—steel which may be hardened and tempered in heavy masses ; abnormal magnetic properties ; variable coefficients of expansion ; high resistance to wear ; resistance to corrosion and acid attack ; and strength and resistance to scaling at high temperatures. By a suitable balance of composition and treatment these special properties can generally be obtained with just those mechanical properties necessary for specific applications. Indeed, the further progressive development of engineering practice, whether it be as regards transportation, power generation, chemical engineering, or in any other direction, is largely bound up in the adequate exploitation of the possibilities now established as regards the properties of alloy steels.

Hitherto, great progress has been made, but through the efforts of individual companies in the industry, which from time to time have produced new steels as a result of work in their research laboratories. Valuable investigations also have been carried out by enthusiastic individuals in the different universities and elsewhere, and the National Physical Laboratory has continuously devoted a proportion of its resources to such work. As regards the researches at Teddington, much encouragement has been forthcoming from the Institution of Mechanical Engineers, whose Alloys of Iron Research Committee, under the chairmanship of Sir John Dewrance, has done much to sustain the work.

It will be a source of satisfaction to the engineering world that the steel industry is now taking what will be regarded as more extensive and adequate steps to ensure, so far as collaboration makes it possible, that the *fundamental* aspect of research, so important as the basis of further progress in this field, is effectively provided for. A joint committee of the British Federation of Iron and Steel Manufacturers and the Iron and Steel Institute has now been appointed which will have the advantage of the assistance of the scientific organisation of the Institute backed in part by the financial resources of the industry. Support is also assured from producers of the raw materials, on the one hand, and from the consuming industries, on the other.

These joint technical committees of the Federation and the Iron and Steel Institute, of which the Alloy Steel Research Committee is one, are of great interest as regards the manner in which they operate. Whilst the constituent companies concerned still rightly jealously preserve full initiative as regards the nature and character of their own products, they fully appreciate the many matters upon which they can usefully collaborate to the advantage of the national industry as a whole. The Committee consists of the leading scientific and technical men in the industry, together with scientists of considerable academic standing along with representatives of the services. Thus the *personnel* is constituted to facilitate a serious attempt not only to endeavour to ensure fundamental research as a basis for further development, but also to encourage a more complete knowledge and understanding of the properties and applications of the steels which are already being produced.

It is astonishing how much we have yet to learn concerning the behaviour and properties of ordinary mild steel. How important is it therefore that every possible step should be taken to hasten the study of the newer steels. It is intended to institute researches under practical conditions, to finance researches in the universities and Government institutions, to assist individual investigators, to suggest programmes of research, and generally by various means at its disposal to encourage progress in the science and technology of special steels. It will be seen that in this case the producers and the users find a community of interest in the programme before the Committee.

The British Federation of Iron and Steel Manufacturers acts in this matter through the Iron and Steel Research Council, which, as is known, is a research association of the Department of Scientific and Industrial Research. Thus we have here another instance where technical and scientific development is being most effectively supported and encouraged by the broadminded and generous policy of that Department. By the present scheme the D.S.I.R. Metallurgy Board's plans as regards this particular field should be effectively taken care of.

Trade Publications.

ALL the great metallurgical industries are now responsible for the publication of scientific and technical information of the utmost value. By their own researches duly presented before scientific societies, by magazines, monthly bulletins, or pamphlets appearing at irregular intervals, they put before the

public the latest information which can have any bearing on the multifarious applications of their products. And, on the whole, they do so in a genuinely scientific spirit. The *Nickel Bulletin* has for years been a very valuable and dependable technical publication for all matters in which the properties of nickel and its alloys are concerned. The International Tin Research Council is producing a useful series of technical pamphlets and the recently published collection of diagrams of the binary alloys of tin is a critical compilation of a high order of scientific merit. The Copper Development Association in its series of Engineers' Note Books is supplying authoritative information, based on research and experience, about copper and copper alloys. Mention may also be made of the scholarly little monograph, "Copper through the Ages," which finds a place in the publications of this Association. These few examples must suffice, though it would be possible to extend the list to cover steel, aluminium, magnesium, and, in fact, almost all branches of metallurgical industry.

All these publications are propaganda, but they are propaganda in the best sense, for they are intended to give publicity to facts. It is true that some discrepancy in outlook is inevitable on account of the commercial rivalry between those responsible for the manufacture and sale of different products, but this need not, and indeed rarely does, result in any discrepancy between their statements and the established facts. At the same time there is bound to be an absence of the judicial balancing of advantages, which consequently devolves upon the user before his final decision can be made. Thus, one group may point to the decided advantages ensured by the use of an undoubtedly efficient though high priced product while another group will concentrate on the possibility, without undue sacrifice of properties, of the substitution or partial substitution of a cheaper constituent for that which is the cause of high price in the first instance. But so long as the facts are truly stated and made available for the purchaser to study, it does not matter very much from what angle they are presented.

This clear indication of the balance between the economic and utilitarian claims of a material is admirably shown in a publication of one of the great steel-producing companies, which contains a "relative price index" of the materials it offers. This is a figure, though admittedly only a rough approximation, giving an indication of the relative cost of various steels, regardless of any changes in the general level of prices. It is frequently of value when a choice has to be made between steels having similar physical properties, when given an appropriate heat treatment in the sizes required. It is a method which might be more widely adopted and applied also to non-ferrous alloys. A "relative price index" of the different aluminium alloys, magnesium alloys, or special brasses would enable a preliminary estimate of value for money to be made with a minimum of trouble.

It is not intended to suggest that costs are the only or even the main factor to be considered. Mr. F. P. Gilligan has stated in the *Journal* of the Society of Automotive Engineers for April, 1935: "Competition is not now confined to the price field, it is a question of quality and service; hence we have the competition of one steel against another, of one alloy against another, and finally and, most important, of the research facilities of one steel company against the research facilities of its competitor." This statement admirably expresses the position except that it does not specifically give credit for the extensive co-operation between different manufacturers, which already exists, in this country at least, through research associations and similar organisations, over wide fields of ferrous and non-ferrous research.

Another development which is very welcome, and indeed which is essential before the intelligent user can exercise the judicial functions referred to, is the disclosure of full details of composition and treatment. Let us by all means have trade names, which are often at first only convenient labels, but which become in course of time guarantees of quality and of uniformity within declared limits. But such names in the past have too often become an excuse for secrecy, and secrecy frequently goes hand in hand with exaggerated claims, some of which can hardly be conceived to have passed the censorship of ordinary intelligence. What we would plead for is a censorship of scientific criticism. It is not the obviously incorrect and exaggerated statements that do most harm. The user will be on his guard. But the *bona fide* statement of opinion based on incomplete or improperly interpreted evidence, or a claim for utility based on guesswork, may waste a lot of valuable time and even do incalculable damage, which in the long run reacts on the producer.

From the user's standpoint the ideal to be sought for in trade publications is not perhaps strict impartiality—this would be asking too much—but scientific accuracy, or, as Mr. Gilligan put it: "More facts and fewer opinions." By scientific editorship, this ideal is being approached to an increasing degree in many industries, and it could be attained if trade publications were all subjected to the same rigid censorship by the scientific directors of the company concerned as similar papers would receive before being admitted to the pages of an independent scientific or technical journal.

Physical Chemistry of Steel Making.

A BOOK under the above title, compiled by Dr. C. H. Herty, jun., and his associates, and published by the Mining and Metallurgical Advisory Boards, Pittsburg, Pa., describes the co-operative work of the United States Bureau of Mines and the Carnegie Institute of Technology on the physical chemistry of steel making. The researches were part of a five-year programme, covering many different aspects of the subject, but directed mainly towards a study of non-metallic inclusions in steel, their nature, properties, methods of determination and elimination, and their direct or indirect effect upon the properties and behaviour of the steel itself. The results of the work have been published from time to time in the form of bulletins, and six consecutive bulletins are selected for publication in the volume under review.

Since Brinell's now classic researches made more than thirty years ago, on the effect of deoxidants on ingot types, data on this subject have been steadily acquired, but it is only in comparatively recent times that the importance of the exact method of deoxidation and the complexity of the factors involved have been fully appreciated. The absence of quantitative control of temperature, and the difficulty of determining the oxygen content, are amongst other factors which have made it impossible to extend the researches described beyond an empirical, practical, type. As Dr. Herty writes in this book: "The metallic elements

present are added as ferro-alloys, and the amount of each element can be closely controlled by the steel-maker. The type of dispersion, however (of non-metallic matter), is controlled by a series of reactions over which control is far from satisfactory. These dispersions are formed when the metal is deoxidised, and the exact type of dispersion depends upon the iron oxide content of the metal before deoxidation, the amounts of the various deoxidisers used, the relative times of their additions, and the degree of fluxing of the particles with each other and with residual dissolved iron oxide following the deoxidation process. Inasmuch as fluxing is of considerable importance, the temperature of the metal must be added as another variable."

Whereas, in the course of many researches into such matters as, for example, the ageing of mild steels, it has been customary to take account only of the steel-making process employed, Dr. Herty has shown that it is further necessary to take account of the precise conditions of working heat. Indeed, differences in working heats by the same process may produce greater variations in the product than similar essential procedure applied to different steel-making processes.

In the first bulletin, No. 64, the author describes the work of the Bureau of Mines on the effect of deoxidation on the rate of ferrite formation in plain carbon steels. The material chosen for the experiments consists of steel billets or axles ranging from 0·33 to 0·50 per cent. carbon content. In the early part of the paper experiments are described which indicate that steels killed with aluminium give more ferrite after air cooling than steels of similar carbon content killed with silicon. The reactivity of steel, defined as " the tendency to change its state due to external application of pressure or change of temperature," is next developed as a mathematical relationship in terms of grain size, degree of supercool, and rate of carbon diffusion. The coefficient of reactivity is calculated for several examples, and is found to be a function of the method of deoxidation. Further, an attempt is made to link reactivity with hardenability.

If established, this would be an important result, but unfortunately the work ceases abruptly at this interesting stage with the phrase : ". . . it is entirely probable that it will be possible to predict the relative hardenability of any steel once the effect of alloying elements on the value of k (coefficient of reactivity) is determined."

In the next bulletin, No. 65, Dr. Herty considers another angle of the same subject, namely, the effect of deoxidation on grain size and grain growth in plain carbon steels. This subject has attained important dimensions in the United States, owing to their intensive production of motor cars, for grain size closely affects the hardenability and machinability, as well as other properties of the steel, and uniformity in these respects is claimed to increase the rate of production whilst lowering production costs. In this research the conclusion is reached that fine grain size is associated with killing the steel with aluminium, whilst the silicon-killed steel is somewhat coarser grained. Similarly, aluminium-killed steel gave small grain size at all rates of heating, whilst in the silicon-killed steels grain growth was considerable at high rates of reheating, but with decreased rate of heating grain refinement was pronounced. In general, the greater the amount of aluminium added in the ladle up to about 0·03 per cent., the finer was the grain ; and steels containing silicon in the range of 0·15 to 0·20 per cent. were finer grained than those containing 0·10 per cent. Aluminium added in the furnace, or as complex alloys, resulted in steels of similar grain behaviour to silicon-killed steels. These results should be interpreted with caution, because the experiments were apparently conducted only upon open-hearth steel, and no work at all seems to have been done on the various types of electric steel, which is employed in this country for the most arduous duty in automobile and aircraft construction.

In passing, one very interesting result is worthy of notice. Two extremely pure iron-carbon alloys in a fine-grained condition and melted under hydrogen were reheated to various temperatures above the critical point. They revealed large and spasmodic grain growth, indicating that the complete absence of impurities permits rapid growth. These steels were also brittle. The whole matter is complicated by the fact that fine grain means high ferrite percentage, good impact strength, and poor machinability. Good machinability, on the other hand, seems to be associated with low ferrite content and brittleness.

Bulletin No. 66 describes the effect of deoxidation on the ageing of mild steel, but although it was found that rimming and semi-killed steels were most susceptible to both quench and strain-ageing, whilst steels properly killed with aluminium did not age, the exact effect of different deoxidation procedures is indeterminate.

Bulletin 67 completes this angle of the research with an interesting investigation into the effect of deoxidation on impact strength of carbon steels at temperatures down to about −40 deg. Cent., in which it was found that rimming and semi-killed steels gave the lowest impact values, whilst properly killed steels in the quenched and tempered condition were best.

In the next bulletin, No. 68, the Bureau of Mines is on less secure ground in a paper on the control of iron oxide in the basic open-hearth furnace. It is well known that every furnace has its own little peculiarities, and " works differently " from its neighbour ; which is simply another method of saying that, although the fundamental steel-making reactions work according to definite principles, which are fairly well understood, there are many factors at work which tend to make an exact quantitative study of the subject extremely difficult.

Nevertheless, Dr. Herty and his associates have produced curves for the equilibria between ferrous oxide and manganese, silicon and aluminium, as well as curves showing the effect of temperature on the solubility of ferrous oxide in iron, the effect of temperature on the distribution of iron oxide between slag and metal, and the oxidising power of gases towards iron at the temperature of melting scrap. They have also developed a quantitative method of determining slag viscosity, which tends to put another important factor in basic open-hearth work on a more precise footing. This work has been carried out under considerable experimental difficulty, and much more pioneer and confirmatory research is required before it can be accepted.

Finally, in the last bulletin, No. 69, Dr. Herty reviews the whole question of the deoxidation of steel. He briefly discusses the various physico-chemical laws which govern the reactions, and then goes on to consider in quantitative terms the equilibria between iron oxide and the three principal deoxidants. Here, again, he is on thin ice. In a laboratory experiment, using materials of carefully controlled com-

position, and working under carefully controlled conditions, it is possible to obtain an approximation to a true chemical equilibrium. In a commercial steel-making furnace, however, it is doubtful if equilibrium is ever obtained, and the situation is more often that of a dozen different reactions all approaching mutual equilibrium under conditions which it is not possible fully to define. In fact, with all the recent advances in pyrometry, it is not yet possible even to measure, with accuracy, the temperature inside a commercial steel-melting furnace.

From this subject the author goes on to a consideration of the various ternary slag systems, MnO-FeO-SiO_2, FeO-SiO_2-Al_2O_3, and the binary systems involving these three oxides; and the three main types of inclusion in rolled steel, visible seams, microscopic seams, and sub-microscopic dispersions. This study is really the crux of the matter, and in the control of the non-metallic matter in steel lies the key to many problems.

The whole book is written with admirable precision and clarity, and herein lies perhaps the greatest danger to the reader. Dr. Herty makes the whole matter look simple, and summarises important issues in a few words. The subjects which he discusses are far from simple, and it is fair to prophesy that the issues which he raises, and many of the facts which he is given to state, will be the subject of eager controversy for many years. Nevertheless, the volume contains a wealth of data, and, interpreted with understanding, is a valuable addition to the library of any student of metallurgy.

Non-Porous Alumina Crucibles.

UNDER the title "A Method for Decreasing the Porosity of Melting Tubes Made of Alumina," T. Satô has published* an account of his investigations based on the discovery made in Professor Andrew's laboratories at Sheffield University, of a method of rendering alundum crucibles less porous. Andrew, Maddocks, and Howat† described their procedure in the following words:—"Alundum crucibles, dried and baked in the usual manner, were soaked for several hours in a saturated solution of magnesium nitrate, *in vacuo*. In this way all pore spaces were evacuated of their air and filled with the saturated magnesium nitrate solution. The crucibles were then dried and baked. The magnesium nitrate became converted into magnesia, and in this way completely filled up all the pore spaces. The resulting material has a very smooth non-porous texture and had little power of absorption for the oxides melted in it."

Satô confirmed this conclusion and determined the extent to which porosity was reduced when the salt used was the sulphate, nitrate, or chloride of aluminium or of magnesium. The temperatures at which these six salts changed completely into their oxides were as follows:—

Salts.	Oxide formation temperature, deg. Cent.
Aluminium sulphate	855
Aluminium nitrate	610
Aluminium chloride	345
Magnesium sulphate	1200
Magnesium nitrate	410
Magnesium chloride	539

Saturated aqueous solutions of these salts were infiltrated into the walls of tubes made of alumina, and the tubes were then heated at temperatures 100 deg. Cent. higher than those at which the oxides were formed. The same treatment was repeated four times and after each treatment the porosity of the tube was measured. For a comparative study of the porosity the tubes were connected to a rotary vacuum pump by means of a rubber tube, and when the number of revolutions of the pump became constant the height of the mercury column in the manometer was read. For the purposes of these experiments the reading was regarded as a measure of relative porosity. The minimum dipping time required to obtain the best results was determined. For the first treatment it varied from thirty minutes for the most highly refractory material to ninety minutes for a less refractory (and less porous) tube; for the fourth treatment of highly refractory tubes three or four times as long was required on account of the decreased porosity of the wall. The results showed that aluminium chloride was the most effective salt, and next came magnesium nitrate and magnesium chloride. With these salts there was little difference in the effect of using cold saturated solutions or hot solutions saturated at 80 deg. Cent.

Porosity was also tested by melting electrolytic iron in the tubes in a Tammann furnace. Carbon monoxide forming the atmosphere of this furnace passes through the wall of a porous tube and is absorbed in the iron. When electrolytic iron was kept at 1600 deg. Cent. for ten minutes under these conditions, its carbon content, originally 0·008 per cent., rose:—

	Per cent.
In alumina tubes as purchased	0·064
After one treatment with $AlCl_3$	0·045
After two treatments with $AlCl_3$	0·036
After three treatments with $AlCl_3$	0·028
After four treatments with $AlCl_3$	0·018

The corrosion of the tubes by molten FeO and molten CuO also diminished as the number of treatments was increased.

Influence of Nitrogen and Oxygen on the Age-Embrittlement of Steel.

THE change in mechanical properties undergone by cold-worked steel on ageing has frequently been held to suggest that age embrittlement of steel is produced by a precipitation process, but the element or elements responsible for the precipitation and the nature of the precipitated material have been the subject of much work and discussion.

The influence of nitrogen and of oxygen on the age embrittlement of steel has now been investigated by W. Eilender, H. Cornelius, and H. Knüppel* at Aachen. They used pure steels made from electrolytic iron, containing carbon 0·03, silicon 0·008, phosphorus 0·001, and sulphur 0·002 per cent. The same material nitrided in ammonia at 600 deg. Cent. was used as a source of nitrogen, and finely divided oxidised electrolytic iron as a source of oxygen, while carbon was controlled by the addition of a very pure melt of Swedish charcoal iron and carbonyl iron with 2·97 per cent. of carbon. Ingots weighing about 700 grammes were forged to 10 mm. square, normalised, and then in part cold-worked 10 per cent. and annealed for half an hour at 250 deg.

* Technology Reports of the Tôhoku Imperial University, Vol. XI (No. 4), pp. 608–619.

† *Journ.*, Iron and Steel Inst., 1931 (2), Vol. 124, p. 288.

**Archiv für das Eisenhüttenwesen*, 1934–35. (May, 1935.) 8, 507.

Cent. Notched bar tests were made in a machine of the Izod type (striking energy 5 mkg.) on test pieces, 6 mm. by 6 mm. by 30 mm., having a 60-deg. V notch, 2 mm. deep and 10 mm. from one end. Nitrogen was determined by the method of Wüst and Duhr,† oxygen by hot extraction in a carbon tube furnace. Results are given of notched bar impact tests on fifty-two steels, as normalised and after cold-work and reheating, together with the percentage fall in impact figure produced by this treatment.

It was first noted, in agreement with the observations of Niedenthal‡ and of Fell,§ that the impact figure of the normalised material with less than 0·01 per cent. of carbon falls as the oxygen content rises (Fig. 1). With higher carbon content the oxygen falls so low that it no longer has any marked effect on the impact figure.

Between oxygen content and susceptibility to age

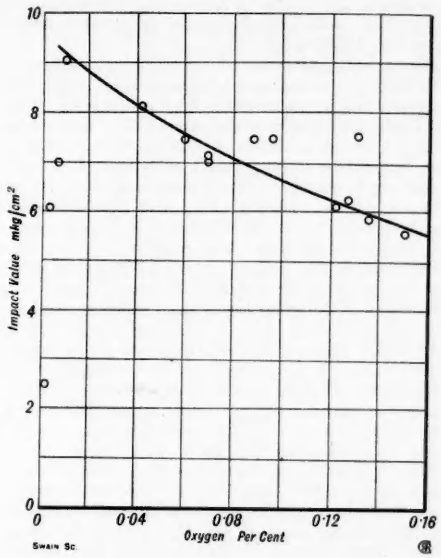


FIG. 1—*Influence of Oxygen Content on the Impact Value (0·005 to 0·009 per cent. Carbon).*

embrittlement no connection was established. There was no effect in steels varying in oxygen which could not be explained by slight differences in nitrogen content.

On the other hand, nitrogen had no clear influence on impact figures in the normalised condition, but at all the carbon contents studied the susceptibility to age embrittlement increased with increasing nitrogen, while, for a constant nitrogen content, it diminished slightly when there was an appreciable increase in carbon.

This is shown in Fig. 2, in which the steels are grouped according to their carbon contents.

These results are in accordance with the idea that age embrittlement is caused by precipitation from a supersaturated solution of nitride, which, on account of either an altered solubility relationship or the presence of more carbide nuclei in the α iron, is less likely to be obtained in steels of higher carbon content. Whatever the explanation, these experiments approach the practical question in a very direct way, and the results seem to be quite definite in showing

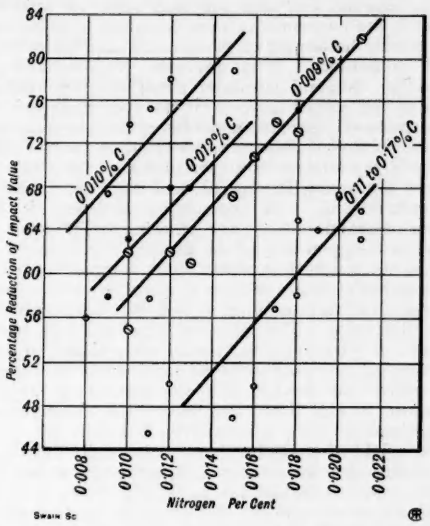


FIG. 2—*Influence of Nitrogen and Carbon Contents on the Reduction of Impact Value produced by Cold-Working 10 per cent. and Heating for Half an Hour at 250 deg. Cent.*

that oxygen has no influence on age embrittlement, though it reduces the impact figure of the normalised steels, but that nitrogen in mild steel increases age embrittlement, while, with constant nitrogen content, an increase of carbon above 0·01 per cent. produces a slight reduction in the susceptibility of the steel to ageing.

Nitrogen Case-Hardening of Steels.

DEVELOPMENTS in the nitride hardening of ferrous materials during recent years have taken the direction of extending the process to engineering steels of many different compositions which were, until recently, not considered suitable for the special hardening treatment. The mechanism of the nitriding of the well-known chromium-aluminium type of nitriding steel (Nitralloy) is now fairly well understood from work that has been carried out by investigators in many countries, and the remarkable surface hardness obtained is considered to be due to the presence of a finely dispersed phase of nitrides, which cause a severe lattice distortion in the α iron lattice and an interference to crystalline slip. This assumption, at least, has served as a good working hypothesis, and the only difference of opinion among workers has, apparently, been a disagreement as to the exact nature of the precipitated nitride phase. Work has recently been carried out at the Tôhoku Imperial University, Japan, to give information on the mechanism of nitride hardening of, chiefly, the Nitralloy type of steel, and is described by S. Nishigori in the Technology Reports of the Tôhoku Imperial University, Vol. XI, No. 4, 1935.

† *Mitt. K.W. Inst. Eisenforschg*, 1921, 2, 39.
‡ *Archiv*, 1929–30, 3, 79.
§ *Archiv*, 1930–31, 4, 393.

The author, in his "Fundamental Investigation on the Nitrogen Case Hardening of Steels," treated nearly 100 carbon-free iron alloys and steels, most of which are of no commercial interest, by nitriding them in ammonia gas at temperatures between 500 and 600 deg. Cent. for various times; the experiments were designed to elucidate the nitride hardening of steels containing chromium and aluminium. The methods of examination included diamond hardness tests, the determination of the weight increase of the specimens due to absorption of nitrogen, a microscopical examination of the nitrided edges after taper-grinding and etching, while X-ray analysis was carried out on various iron alloys containing Cr and Al, and on a specimen of Nitralloy steel. An exhaustive account of the experimental details is given, showing the influence of time and temperature on the depth of hardening, &c., while not fewer than thirty-eight composite photomicrographs, mostly of carbon-free alloys which were nitrided for various times at different temperatures, are illustrated. The influence of aluminium, chromium, molybdenum, and nickel when added to iron in varying amounts were examined, and the effect of carbon was studied in steels containing varying amounts of aluminium and chromium. Most of the experimental work described is, however, not new, as the field of study has been rather fully exploited during the last few years; it is, therefore, surprising that many experimental facts which are now so well known should at this stage be published in such detail, as such examples of overlapping of research could be avoided by a study of the literature. Many of the experiments described by the author have been carried out in this country, and published in 1932 by Jones and Morgan ("Investigations into the Nitrogen-hardening of Steels," Part I, Iron and Steel Institute, Carnegie Scholarship Memoirs, Vol. XXI, page 39), which work the author has apparently overlooked, and, more recently, by Jones ("Investigations into the Nitrogen-hardening of Steels," Part II, Iron and Steel Institute, Carnegie Scholarship Memoirs, Vol. XXII, 1933, and Parts III and IV, Vol. XXIII, 1934).

Most of the work described by the author was not designed to give much new information and is therefore open to criticism in many respects. The experimental method of nitriding described included certain academic refinements which were unnecessary, and did not include even such a simple adjunct to the equipment as a Dissociation Pipette for measuring the percentage dissociation of the exit gases. Some of the conclusions reached—for instance, "the dissociation of ammonia gas in nitriding of steels is mainly due to catalytic reaction of the surfaces of the specimens" and "the consumption of ammonia gas increased as the nitriding temperature became higher" appear to be merely a reiteration of simple facts which have been well known for years. The nitriding of the carbon free alloys showed that the weight increase, due to absorbed nitrogen, was greatest in the iron-aluminium alloys; these were found also to harden to the greatest extent, while iron alloyed with molybdenum ranked second in hardness. The weight and hardness of the iron-chromium alloys increased with greater additions of chromium, the greatest depth of hardening, however, being found in alloys containing 2 per cent. of the element. Chromium and aluminium, added jointly to iron, induced great hardness when the aluminium reached 1 per cent. The interesting fact was found that the nitriding of alloys in the absence of carbon caused them to disintegrate into powder when the aluminium and chromium content reached the values found in Nitralloy steel, and this is considered to be due to the formation of a nitride containing iron, aluminium, and chromium, which caused a great volume expansion. The well-known fact that iron-nickel alloys do not harden (Jones, *vide supra*) was confirmed, but the conclusion reached, that "the hardness in their outer skin decreased, because the iron oxide mingled during the melting was reduced by the active H_2 gas produced by dissociation of NH_3 gas" is not of interest to even the keenest theorist. The effect of carbon on the weight increase and hardening in aluminium steels was found to be very slight, but the effect of carbon on the hardening properties of chromium steels was very great. The conclusions, that in the chromium-aluminium steels the depth of case decreased as the carbon content became greater; that aluminium determined mainly the maximum hardness, and the amount of chromium determined the depth of hardening, are conclusions which have been already described in the work of Jones and Morgan (*loc. cit.*).

The microstructures of the nitrided carbon-free iron alloys containing aluminium, chromium, molybdenum, and aluminium-chromium were studied in an attempt to explain the structure of the nitrided parts of nitriding steels containing these elements. The specimens were ground at an angle of 3 or 9 deg. and etched before examination. It was found that the structures of the iron-aluminium alloys were similar to those of the iron-molybdenum alloys, both showing the presence of a white needle phase distributed in a "Widman-stätten" pattern in a deep brown ground mass. The structures of the very low iron-aluminium (0·44 per cent. Al) alloys were similar to those of pure iron, the outer Fe_2N phase (ε) being followed by a band of Fe_4N (γ') and α iron which contained needles of γ'. With higher aluminium the γ' phase apparently was not the same as that appearing in the iron-nitrogen system, and new lines discovered by X-ray analysis mean possibly that the phase resembling γ' is a ternary compound composed of iron, aluminium, and nitrogen. The iron-nickel alloys were similar to pure iron, and the iron-chromium alloys also showed a similar structure, except that the nitride needles were absent, observations which confirm the work of Jones. The structure of the iron-aluminium-chromium alloys were similar in type to the iron-aluminium alloys, although the disintegration of some of the alloys was due apparently to the presence of a phase at the grain boundaries. The influence of carbon on the alloys was to cause a marked refining of the structure.

The most interesting part of the investigation is described in the later stages of the publication on X-ray analysis. This was carried out on twelve carbonless alloys, a 0·74 per cent. carbon steel, and a chromium-aluminium steel, by means of the Debye-Scherrer method, using an iron anticathode. The specimens were nitrided for two, five, ten, and fifteen hours at 500 deg. Cent. The results are given in Table I.

The kinds of lines appearing in the X-ray films are represented by the letters α (body-centred cube, same kind as that of α iron), γ' (face-centred cube, same kind as that of Fe_4N), ε (hexagonal close-packed lattice, same kind as that of Fe_2N), ε' (new phase discovered, whose crystalline structure has not yet been determined). From X-ray analysis the alloys can be classified into four groups:—

(1) Same as pure iron (specimens Nos. 1, 2, 3, 9A), where γ' and ε gradually increase as the nitriding time

becomes longer. The specimens nitrided for more than ten hours show only the lines of ε.

(2) Similar to (1), but the lines appearing in the film of the specimen nitrided for two and five hours are much diffused (specimens Nos. 4, 5, 6.).

(3) The iron-aluminium alloys. ε′ appears in the surface of the specimens nitrided for more than five hours (specimens Nos. 7, 12, 16, 19, and 21).

(4) Similar to (3), but all the lines become faint and diffused (specimens No. 8 and X).

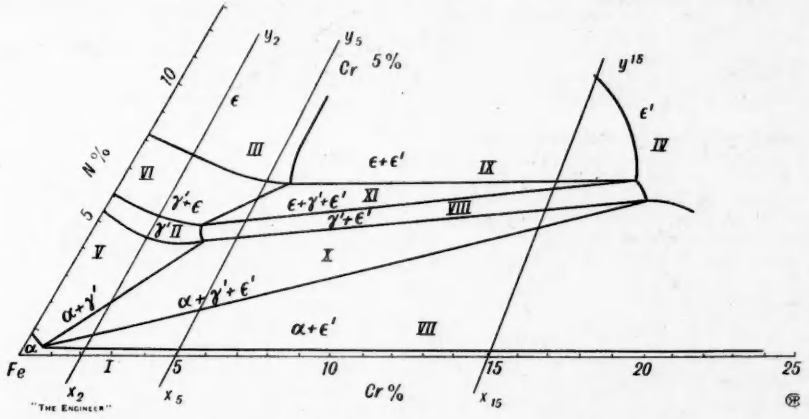
The results obtained have been used in conjunction with the results of the investigation by Jones ("Investigations into the Nitrogen-hardening of Steels," Part II, *loc. cit*), who reported a special phase (a ternary compound of iron, chromium, and nitrogen) found on nitriding high-chromium steels. These have formed the basis for the construction of a structural diagram of the iron-chromium-nitrogen system at the nitriding temperature (500 deg. Cent.), shown in the accompanying graph.

It is assumed that the range of composition of ε′ is shown by field IV, and the ranges of ε and γ′ in the ternary system are shown by fields III and II. Fields I, II, III, and IV consist of single phase (α, γ′, ε, and ε′ respectively), fields V, VI, VII, VIII, and IX consist of two phase (α+γ′, γ′+ε, α+ε′, γ′+ε, and ε+ε′ respectively), while fields X and XI consist of three phases (α+γ′+ε′ and ε+γ′+ε′ respectively). The composition of the nitrided cases is expressed by the line connecting the points of per cent. chromium (say, 2, 3, and 5 per cent. chromium) on the iron-chromium side with the point of 100 per cent. nitrogen, because the ratio Fe : Cr must be constant in the nitrided case; the points on the lines $x_2\,y_2$, $x_5\,y_5$, and $x_{15}\,y_{15}$ represent the structures appearing in the nitrided cases. The author states that the structures of the nitrided parts of the iron-aluminium alloys obtained from the experiments can also be explained qualitatively by using the same kind of diagram, if the ranges II, III, IV are shifted to the lower percentage of aluminium, the assumption being reasonable as the atomic weight of aluminium is much smaller than that of chromium. In the low alloy steels studied the author concludes that hardening is due in the inner parts of aluminium and chromium steels to a disturbance of the α iron lattice induced by the formation of the fine ternary compound, the ε′ phase, in the α iron matrix. The great hardness, however, of the outer parts of the iron-aluminium alloys, Nitralloy steel, and of high-chromium steels is due to the great hardness of ε′ itself. The important information obtained from the X-ray analysis does not con-

Nitrogen Case-Hardening for Steels.

Specimen No.	Chemical Composition. C.	Al.	Cr.	Hardness.	Results of X-ray analysis. Not nitrided.	Two hours nitrided.	Five hours nitrided.	Ten hours nitrided.	Fifteen hours nitrided.
1	—	—	—	O	α	α+γ′	α+γ′+ε	ε	ε
2	—	—	0·73	O	α	α+γ′	α+γ′+ε	ε	ε
3	—	—	1·53	×	α	α+γ′	α+γ′+ε	ε	ε
4	—	—	2·87	×	α	α (diffused)	ε+? (diffused)	ε	ε
5	—	—	3·41	×	α	α (diffused)	ε+? (diffused)	ε	ε
6	—	—	4·95	×	α	α (diffused)	ε+? (diffused)	ε	ε
7	—	0·79	—	O	α	α+γ′	ε′+γ′+α	ε′+γ′+ε	ε′+γ′+ε
8	—	0·82	1·01	×	α	α (diffused)	ε′+? (diffused)	ε′+γ′+ε	ε′+γ′+ε
12	—	1·58	—	O	α	α+γ′	ε′+γ′+α	ε′+γ′+ε	ε′+γ′+ε
16	—	2·65	—	×	α	α+γ′	ε′+γ′+α	ε′+γ′+ε	ε′+γ′+ε
19	—	3·72	—	O	α	α+γ′	ε′+γ′+α	ε′+γ′+ε	ε′+γ′+ε
21	—	4·75	—	×	α	α+γ′	ε′+γ′+α	ε′+γ′+ε	ε′+γ′+ε
9A	0·74	—	—	O	α	α+γ′	ε+γ′+α	ε	ε
X	0·37	1·47	1·58	×	α	α (diffused)	ε′+γ′ (diffused)	ε′+γ′+ε	ε′+γ′+ε

Specimens marked O could be filed; those marked × could not be filed.



Structural diagram of iron-chromium-nitrogen at the nitriding temperature.

firm the views of Fry (*Journal* of the Iron and Steel Institute, 1932, No. 1, p. 191), or of Norton (American Institute of Mining and Metallurgical Engineers, Technical Publication No. 550), who believe that the distortion of the lattice is caused by the formation of insoluble alloy nitrides only, such as aluminium nitride or chromium nitride. The evidence of the new phase, however, confirms appreciably the work of Jones, who showed that the finely dispersed nitride particles consist of a complex nitride of iron which contains the alloying elements.

The Zinc Iron Equilibrium Diagram.

By W. D. JONES, M.Eng., Ph.D., and R. T. PARKER, B.Sc., A.R.S.M., A.I.C.

THE systems iron-zinc, iron-antimony, and iron-arsenic present unusual difficulties to the investigator. Owing to the high melting point of iron and the low boiling points and high volatility of zinc, arsenic, and antimony, homogeneous alloys suitable for metallographic examination are almost impossible to obtain, at least at the iron ends of the diagrams. In recent years improved technique, embracing the use of high pressures and induction heating, has afforded the means of a complete survey of these three systems. It might be thought that advantage would have been taken of such possibilities, particularly in the case of the iron-zinc system, the association of which with galvanising, sherardising, &c., gives it considerable industrial importance.

A detailed study of the literature upon the subject of the constitution of the iron-zinc alloys has established the view that very considerable work is needed upon this subject. Many of the available data are either unconfirmed or else mutually contradictory, not necessarily on account of faulty technique, but possibly owing to wrong interpretation of experimental results.

An account of previous investigations of importance upon iron-zinc alloys has been compiled, and although this survey does not embrace any fresh experimental work, the authors feel that the publication of it may be of service in enabling a rapid appreciation to be made of the present position of the subject.

Work upon this constitutional diagram was initiated by A. von Vegesack (1), who investigated those alloys containing up to 24 per cent. iron by thermal and microscopic methods.

Reference to Fig. 1 shows that the partial diagram incorporating Vegesack's experimental results had the following salient features :—

(1) Solid solubility of iron in zinc up to about 0·7 per cent. iron.

(2) From 0·7 per cent. to 7·3 per cent. iron was a region of solid solutions between zinc containing 0·7 per cent. iron and (3).

(3) From 7·3 per cent. to 10·9 per cent. iron a region of varying proportions of zinc and $FeZn_7$.

(4) Between 10·9 per cent. and approximately 22 per cent. iron the structure consists of $FeZn_3$ and $FeZn_7$ crystals in varying proportions.

The views of P. T. Arnemann (2) on the diagram were practically identical with those of Vegesack.

U. Raydt and G. Tammann (3) made a comprehensive study of the system, and, in order to overcome the difficulties due to the vaporisation of zinc at higher temperatures, they worked under pressures extending to 130 atmospheres. In general, Raydt and Tammann confirmed the work of Vegesack, except that they found, in addition, a solid solution of zinc in iron with a saturation point at about 80 per cent. iron.

Little further progress was made in the elucidation of the diagram until W. M. Peirce (4, 5) and L. H.

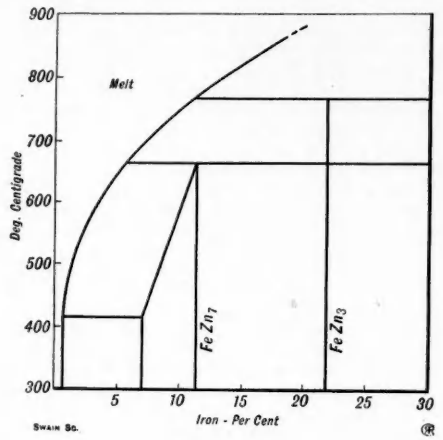


FIG. 1

Marshall (5) re-investigated the zinc end of the system. They agreed with the main outlines of the existing diagram, but observed that the portions extending beyond 25 per cent. iron were based on inadequate data and needed further investigation. These workers had confined themselves to the region 0 per cent. to 17 per cent. iron and established the features of this range more firmly. Additionally it

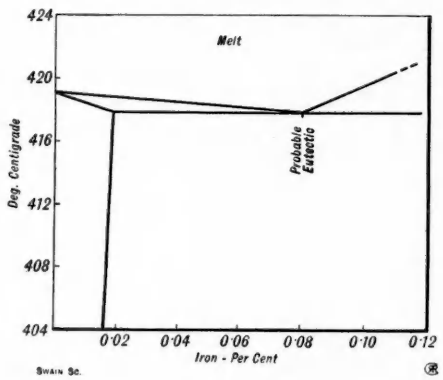


FIG. 2

was found that the solid solubility of iron in zinc extended from 0·02 per cent. at the melting point of zinc down to 0·008 per cent. at room temperature—see Fig. 2. Moreover, it was found that there was some evidence of an eutectic arrest at 418 deg. Cent., corresponding, upon their provisional diagram—Fig. 2—to about 0·08 per cent. iron, although they pointed out that this eutectic composition was an unknown composition at the time of the publication of their results. This eutectic would no doubt have

(Zn, Fe) and (Zn, $FeZn_7$) solid solutions as its structural components.

A further modification of the diagram has recently been made by W. D. Jones (6). Using a diffusion technique employing powdered zinc and iron, this investigator has shown that the range of solid solution at the iron end of the diagram contains a "gamma loop." This places the iron-rich alloys of zinc among the range of alpha alloys, which includes iron-chromium, iron-silicon, iron-beryllium, &c.

Such is the manner in which the present form of the diagram has been derived; it will be interesting to see how data collected from other types of investigations correspond with it.

S. Wologdine (7) studied alloys containing from 0 per cent. to 10 per cent. iron and stated that the first iron-zinc compound was of composition $FeZn_{10}$. This he established by dissolving excess zinc from an alloy consisting of crystals of the compound plus a little zinc, and analysing the remainder.

W. Guertler (8), in an investigation of the structure of zinc-coated iron, supplied a diagram from his "Handbook of Metallography." This was essentially the same as that of Vegesack, except that the region between 24 per cent. and 100 per cent. iron was

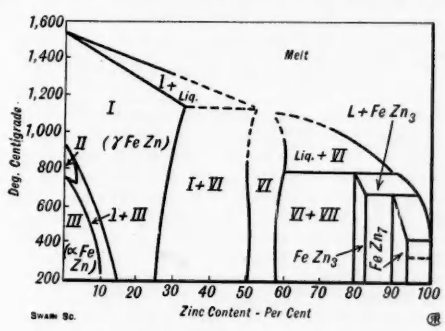


FIG. 3

occupied by several phases of unconfirmed constitution. Thus between 40 per cent. and 50 per cent. iron —see Fig. 3—was placed an intermediary phase of unknown composition—VI; between 75 per cent. and 100 per cent. iron were solid solutions of zinc and iron—I, &c.; and between 50 per cent. and 75 per cent. iron a phase of varying proportions of I and VI. Another point of interest about this diagram is that $FeZn_3$ was proposed to have a range of composition approximately 19 to 21 per cent. iron.

Vigouroux, Ducelliez, and Bourbon (9) investigated the iron-zinc alloys by means of solution potential methods and found four compounds. These were $FeZn_7$, $FeZn_3$, Fe_3Zn, and Fe_5Zn; that is, two more compounds than are provided for by the generally accepted diagram. The compound Fe_3Zn was represented by a very marked increase in E.M.F. in Vigouroux, Ducelliez, and Bourbon's diagram, while the Fe_5Zn compound was less marked.

E. Lehmann (10) investigated the magnetic properties of the zinc-iron alloys and found a very pronounced maximum at 7·3 per cent. iron, which corresponds approximately to $FeZn_{11}$. Unfortunately, this investigation was not applied to alloys with more than 9·0 per cent. iron, or a very useful contribution to our knowledge of the diagram might have been made.

More recently, Tammann and Rocha (11) suggested modifications of the zinc-iron diagram. The work of these investigators was conducted by diffusion between powdered zinc and iron and by dipping iron strips into molten zinc. Thus they found the following layers in the coating of one iron strip:—

(*a*) Zinc, outer coating.
(*b*) Solid solution "B," $FeZn_7$.
(*c*) Crystals of "C," $FeZn_3$.
(*d*) A layer of unknown composition "D."
(*e*) The iron base.

Moreover, on annealing for over four hours at 350 deg. Cent. a fourth layer appeared between (*d*) and (*e*), and this was designated as "E" and regarded as an iron-rich solid solution.

Ogawa and Murakami (12) attempted to revise the whole of the diagram and made the following suggestions. Firstly, they held that the compound regarded as $FeZn_3$ is more nearly represented by the formula Fe_3Zn_{10}, the evidence for this statement being based on data obtained from X-ray investigations. Secondly, at the iron end of the diagram they found the solubility of zinc in iron to be 18 per cent., and proved, by electrolytic solution pressures of suitable alloys, that Fe_3Zn and Fe_7Zn did not exist.

C. W. Stillwell and G. L. Clark (13) and Osawa and Ogawa (14) used X-ray technique to investigate the nature of the layers produced by dipping iron into molten zinc. It is more convenient to tabulate their findings for comparative purposes:—

Stillwell and Clark.			Osawa and Ogawa.		
Close packed hexagonal	A	$FeZn_7$	Hexagonal	ε	Zn in $FeZn_7$
Do. do.	B	Isomorphous with zinc			
Body centred..	C	Not explained	Body centred	β	$FeZn_3$
			Face centred	α	$FeZn_3$·Fe

While it is admitted that these X-ray investigations have not brought forward any definite new compounds, yet it is clear that there is not even agreement upon those already known to be present. With the equilibrium diagram in such a state of uncertainty it is not surprising that the interpretation of galvanised and other zinc coatings is a difficult matter.

J. L. Scheuler (15), examining the structure of zinc-coated wire, held that the microscopic methods of identification were difficult to apply and therefore preferred an analytical method. By solution of different layers of coating and subsequent analysis this investigator found the structure essentially consisted of $FeZn_{10}$, $FeZn_7$, $FeZn_3$, and zinc in the proportions 3 : 14 : 60 : 23. In discussion of the same work, O. W. Storey claimed that he had separated crystals of $FeZn_{10}$ and proved their composition as such. In this connection he agreed with S. Wologdine (7).

H. Grubitsch (16), in a similar investigation, found $FeZn_3$ and $FeZn_7$ layers, and also a rich iron alloy layer, which was ascribed to diffusion, next to the iron base. This latter alloy appeared more especially with the use of high-carbon steels; it may be one of the extra compounds found by Vigouroux, Ducelliez, and Bourbon.

W. H. Finkeldey (17) and H. S. Rawdon (18) both held the view that the structure of hot dipped zinc coatings on iron was essentially of zinc, $FeZn_7$, and $FeZn_3$, the last-named being adjacent to the ferrous metal base.

H. Bablik (19), however, in a diagrammatic explanation of the coating (after Guertler), states that next to the iron is a diffusion layer of 80 per cent. iron

content, and then a layer of 11 per cent. to 22 per cent. iron, which is of composition $FeZn_3$ to $FeZn_7$.

Thus it will be seen that the zinc end of the diagram is well established, except in so far as Peirce and Marshall's suggested eutectic at 0·08 per cent. iron is yet to be confirmed. Above 24 per cent. iron the diagram is very vague, although the mass of the evidence points to the existence of another compound.

In conclusion, it may be added that here is a subject for research which will be of both academic and industrial interest, and upon which we expectantly await information. Not only will such work settle the problem of the true constitution of zinc-iron coatings, &c., but the experimental technique used will no doubt be of great use in elucidating the alloy systems of iron with other easily volatilised metals.

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Copper Steel Castings.

COPPER steels, which have attracted attention on account of their capacity for hardening by precipitation of copper, have been considered as possible materials for steel castings in a paper entitled "Hardenable Copper-Alloy Cast Steel," by E. Söhnchen and E. Piwowarsky.* The authors describe the properties of cast Bessemer and electric furnace steels of the approximate composition—carbon 0·25, manganese 0·7, silicon 0·3 to 0·4 per cent., with copper either 0·1 or 0·9 per cent. The materials containing 0·9 per cent. of copper reach a Brinell hardness of about 200 when the cast annealed steel has been reheated at 500 deg. Cent. for five hours, and a slightly greater hardness after eighteen hours at 450 deg. Cent. (Fig. 1). The maximum hardness reached after heating at any given tempering temperature was always a little higher for the Bessemer than for the electric furnace steel, but the time taken to reach the maximum hardness was about the same for each. In practice the most desirable heat treatment would be that which gives the maximum effect after heating at the lowest possible temperature for the shortest time. Comparative tests showed that the rate of heating had an important influence. Specimens heated up with the furnace attained their greatest hardness more quickly than those charged into a furnace at the required temperature (Fig. 2).

* *Die Giesserei*, March 1st, 1935, Vol. XXII, pages 96–100.

These few experimental results complete the direct references, made in the paper, to cast steels. There follows a discussion of the effect of added elements in which some interesting observations are collected together from different sources, but the conclusions are all drawn from work on forged or rolled steels. With change of composition there is a change in the solubility of copper in α iron, and this has its effect on the degree of precipitation hardening. Thus,

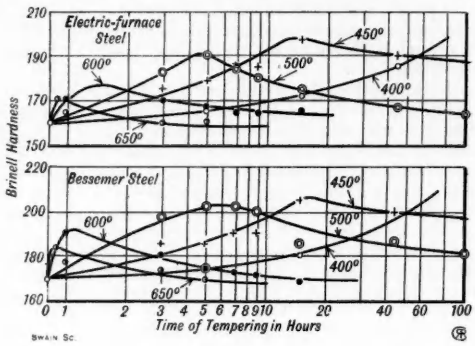

FIG. 1—*Effect of Tempering of Cast Steel with 1 per cent. of Copper (Annealed at 930 deg. Cent.).*

carbon reduces the extent to which precipitation hardening is observed, though Eilender, Fry and Gottwald* have shown that after the addition of titanium a 0·3 per cent. carbon copper steel hardens as much as one with 0·1 per cent. carbon. Nickel reduces the hardening effect of copper to a slight extent, and manganese and silicon do so in a marked degree. Additions also affect the copper percentage which is necessary to secure precipitation. Thus, in the presence of 0·2 per cent. of molybdenum, hardening of the copper steels sets in when the copper is only 0·4 per cent.

The tempering treatment results in a rise of tensile

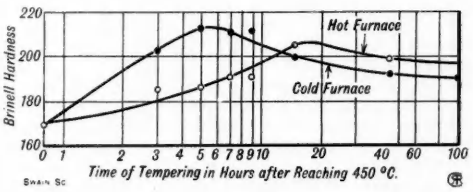

FIG. 2—*Influence of Rate of Heating on the Precipitation of Copper in Cast Steel.*

strength and especially of yield point, so that the yield ratio is proportionately increased. Brittleness, as measured by the notched bar test, is greatly increased, but the difference between carbon steel with and without copper and between copper steel before and after the tempering treatment, is less marked at raised temperatures, for example, above 100 deg. Cent. The authors emphasise several advantages which the copper steels are said to possess, notably resistance to atmospheric corrosion, which, according to Carus and Schulz, is due to the formation on the corroding surface of a copper-rich

* *Stahl und Eisen*, 1934, 54, 559.

protective film which protects the surface from further attack.

Although the paper by Söhnchen and Piwowarsky is a useful indication of the probable properties of copper alloy steels in the cast condition, the authors advisedly use the term "cast steel" and not "steel castings" in the title, since they express no opinion as to the degree of success which would attend the introduction of this element into the composition of a steel used for actual castings.

Such questions as fluidity or "life," liquid and solid contraction, tendency to tearing and action on the sand, are of essential importance, and would have to be settled before the use of such steels could be recommended. If the steels proved to be satisfactory in all these respects, there would be some hope of producing good copper steel castings, and the method of treatment by which hardening is secured might also have advantages since the reheating which forms an essential part of the treatment would also remove residual stresses; but by no means all the possible objections to their use would even then have been overcome. There remains, for example, the fact that the impact figure of temper-hardened carbon-copper steels at atmospheric temperature is very low. It is true, as the authors point out, that at temperatures above 100 deg. Cent. the impact figure is not very different from that of untreated copper steel or steel free from copper, and that the impact figure/temperature curve is merely displaced a little to the right by the addition of copper. But in practice this displacement means that, at atmospheric temperature, there is a fall of 50 per cent. in the impact figure of the electric furnace steel and of about 75 per cent. in that of the Bessemer steel for a gain of a little over 20 per cent. in tensile strength, and only at the cost of sacrificing this gain in strength can the impact figure be restored.

The fact that low carbon copper steels show the most pronounced hardening is interesting, but not economically significant, unless the properties of these steels should be actually better than those of their competitors. Castings are purchased for their final properties, and not for the degree to which they respond to a particular form of heat treatment. Apart from technical difficulties therefore the economic adoption of copper steels for castings will depend on whether they give properties equal to or better than those obtained in ordinary hardened and tempered steels at equal cost.

Some of these points are touched upon in a paper on "The Properties of Some Cast Alloy Steels," by T. N. Armstrong.* Included in a long series of cast steels of low alloy content were the copper-bearing steels shown in Table I. The properties of these steels were recorded after a variety of heat treatments, the results of some of which are shown in Table II. Although the tensile strength was not appreciably raised in comparison with copper-free steels, the yield ratio was always increased by copper and the impact figure remained high in the normalised and tempered condition. Temper hardening was not systematically investigated, and the main interest of the paper in relation to the foregoing comments on the work of Söhnchen and Piwowarsky is the statement by the author: "Copper segregation can be noticed in risers and around the grains exposed by hot tears in copper-bearing steels. Possibly this copper segregation is a contributing cause to these hot tears in steel containing high copper, and until there is some conclusive evidence that copper not retained in solution does not cause castings to crack, copper steels will never be very popular with foundrymen." (It was explained later that the word "segregation" in this sentence was intended to refer, not to segregation on freezing, but to copper separation from solid solution.) The statement that copper may cause hot tearing, and the evidence on which it was based, was strongly contested in the discussion which followed. The copper-coloured surface, visible in risers and around the grains exposed by hot tears in copper-bearing steels, was attributed to the preferential oxidation of the iron. In other words, the appearance of copper on the surface of the hot tears is the result of an action occurring after the tears have actually formed. Only one copper-silicon-manganese steel (No. 10) was investigated by Armstrong, but tests on similar material of higher copper content,

TABLE I.—*Composition of Copper-bearing Cast Steels investigated by T. N. Armstrong.*

Steel No.	C.	Si.	Mn.	Ni.	Cu.
9	0·28	0·21	0·75	—	0·82
10	0·15	1·09	1·43	—	0·34
11	0·27	0·34	0·99	1·26	1·17
12	0·24	0·31	1·02	—	1·26

TABLE II.—*Mechanical Properties of Copper-bearing Cast Steels Investigated by T. N. Armstrong.*

Steel.	Treatment.	Yield point, tons/sq. in.	Tensile strength, tons/sq. in.	Elongation, per cent.	Reduction of area, per cent.	Izod impact figure ft.-lb.
Cu-Mn (No. 9)	As cast	29·4	43·0	17	23	8
	Ann. 900 deg. Cent.	26·3	35·7	28	50	40
	N. 900 deg., T. 650 deg. Cent., 2 hours	26·6	36·5	28	55	40
	Double N. 900 deg., T. 650 deg. Cent., 2 hours	28·9	37·4	28	54	50
Cu-Mn-Si (No. 10)	As cast	47·4	51·3	1	1	3
	Ann, 900 deg. Cent.	27·3	38·6	30	60	10
	N. 900 deg., T. 650 deg. Cent., 2 hours	25·9	37·7	30	63	24
	Double N. 900 deg., T. 650 deg. Cent., 2 hours	26·6	39·3	30	63	43
Cu-Ni-Mn (No. 11)	As cast	31·6	44·7	15	19	5
	Ann. 900 deg. Cent.	30·8	43·0	25	40	34–42
	N. 900 deg., T. 650 deg. Cent., 2 hours	31·0	42·9	25	53	29–38
	Double N 900 deg., T. 650 deg. Cent., 2 hours.	32·7	42·4	25	52	43
Cu-Mn (No. 12)	As cast	31·9	40·6	12	18	5
	Ann. 900 deg. Cent.	26·3	37·3	25	43	40
	N. 900 deg., T. 650 deg. Cent., 2 hours	29·0	39·5	26	57	29–47
	Double N. 900 deg., T. 650 deg. Cent., 2 hours	32·5	39·0	25	57	62

* "Trans.," Amer. Soc. for Metals, 1935, 23, 286–318.

communicated by A. Finlayson, of the Pacific Car and Foundry Company, Seattle, Washington, showed that these steels have excellent properties if the carbon is kept below 0·2 per cent. With copper 1·75 to 1·9 per cent., the yield point varied from 27 to 35, and tensile strength from 38 to 42 tons per square inch, the elongations being 23 to 33 and the reductions of area 40 to 60 per cent. The danger point of copper in such compositions was put at 2·5 per cent., whereas Armstrong put it at 1 per cent. It was stated, moreover, that in a large output of such steel for commercial castings, ranging in weight from 3 lb. to 7 tons, made during the last six years, no unusual difficulty had been experienced and the alloys showed no special tendency to tear.

This record places the future of copper steel castings in a favourable light and encourages the view that further examination should be made of the modification of their properties by temper hardening on the lines indicated by Söhnchen and Piwowarsky.

Chromium Steels.

IN a recent paper, W. Tofaute, A. Sponheuer and H. Bennek* have discussed the constitution and the behaviour on hardening and tempering of steels containing up to 1 per cent. of carbon and 12 per cent. of chromium. Their experiments were carried out on twenty-three high-frequency furnace steels, the critical ranges of which were determined by thermal and dilatometric methods and checked by hardness tests made on the steels quenched at temperatures between 725 deg. and 1300 deg. Cent. By the use of the dilatometric results and by microscopical examination of the quenched specimens and of others quenched from higher temperatures five sections of carbide $(CrFe)_7C_3$ as a determining factor in the behaviour of chromium steels on heat treatment. This carbide, they state, first appears in steels with chromium increasing from about 2·5 to 4 per cent. as the carbon rises from 0·1 to 1·5 per cent. The

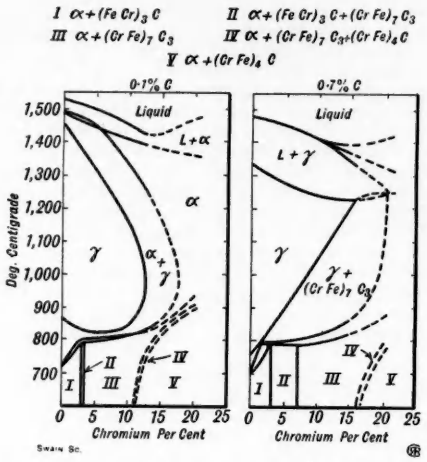

FIG. 1—*Sections of the Iron-chromium-carbon Diagram. (Carbon 0·1 and 0·7 Per Cent.)*

velocity of cooling necessary for hardening is lowered by increase in chromium, but the maximum hardness attained is dependent on the carbon content. In hypereutectoid steels the maximum hardness can only be reached by quenching from the temperature indicated by the solubility surface of $(CrFe)_7C_3$ in

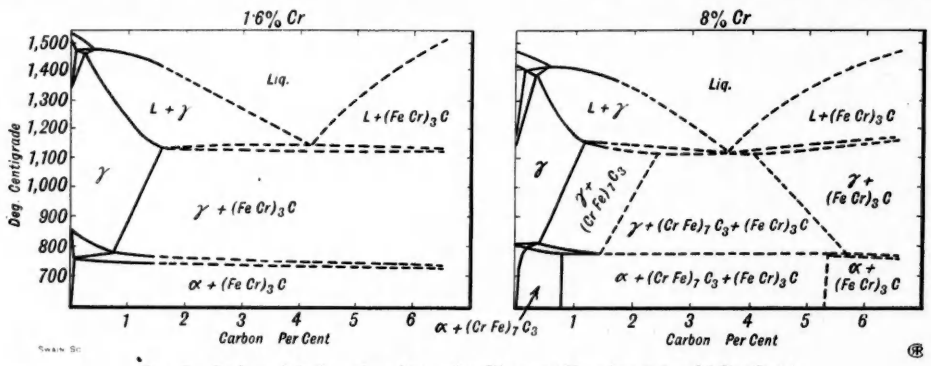

FIG. 2—*Sections of the Iron-chromium-carbon Diagram (Chromium 1·6 and 8 Per Cent.)*

the iron-chromium-carbon diagram with constant carbon content, and five with constant chromium content were constructed. In the interpretation of the diagram the existence of $(FeCr)_3C$, $(CrFe)_7C_3$, and $(CrFe)_4C$ was accepted on the basis of the work of Westgren and others. Typical diagrams from among the ten given are shown in Figs. 1 and 2, but the originals should be consulted for greater detail and for indications of the experimental evidence on which they are based.

The authors attach very great importance to the γ-solid solution. The hardness of steel specimens 20 mm. in diameter and 20 mm. long, quenched in water after one to two hours at 725 deg. to 1300 deg. Cent., is shown in Fig. 3. "Testor" hardness is said to bear to Rockwell "C" hardness the ratio of 10 to 9.

The "mass effect" in chromium steels was studied in more detail in a special series containing 0·4 and 1·0 per cent. carbon with chromium up to 3 per cent. These were water-quenched from 900 deg. Cent. in pieces 60 mm. in diameter and 120 mm. long. The depth of hardening increased with increase of chromium content and with about 3 per cent.

* *Archiv für das Eisenhüttenwesen*, 1934–35 (May, 1935), 8, 499–506.

chromium the hardening was uniform throughout the section—Fig. 4. This chromium content was noted to represent the limiting composition in which $(CrFe)_7C_3$ was present in solid solution at high temperatures.

To investigate the retardation of tempering produced by chromium, two series of steels containing 0·4 and 1·0 per cent. of carbon were quenched from

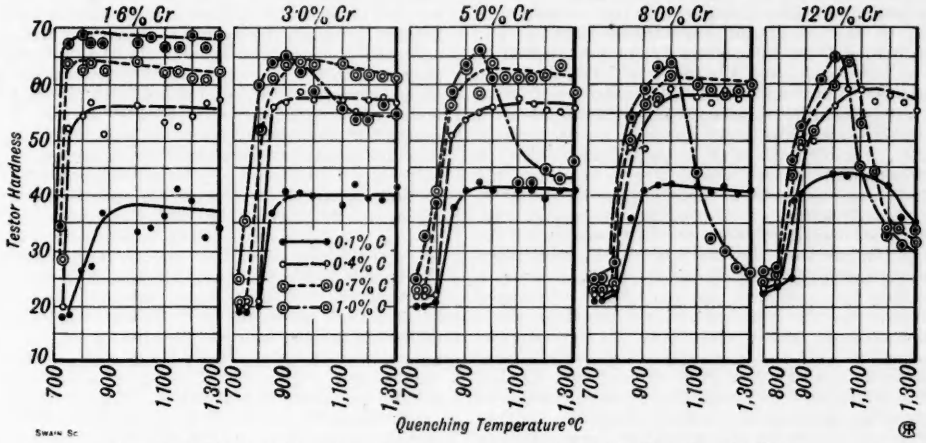

FIG. 3—*Hardness of Chromium Steels Quenched from* 725 *to* 1300 *Deg. Cent. in Water.*

different temperatures between 850 deg. and 1100 deg. Cent. and tempered at various temperatures from 300 deg. to 700 deg. Cent. In all sixty curves of hardness against tempering temperature are given, but the behaviour of the steels may be illustrated by the selected curves in Fig. 5. The chromium-free steels showed a gradual fall of hardness as the tempering temperature rose, and the same conclusion

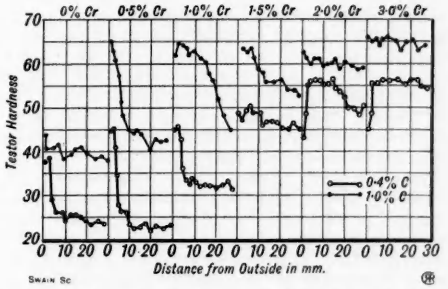

FIG. 4—*Hardness through Sections of Chromium Steels,* 60 *mm. Diameter, After Water Quenching from* 900 *Deg. Cent.*

applied to steels with 1·6 per cent. of chromium. In the 3 per cent. chromium steels, however, the rate of fall of hardness with increasing tempering temperature was checked at tempering temperatures of 400 deg. to 500 deg. Cent. The authors attribute this increased resistance to tempering to the precipitation of the special carbide, in a manner similar to that shown to occur in tungsten and vanadium steels by Houdrement, Bennek and Schrader.† In the lower range of tempering temperatures (about 300 deg. Cent.) the martensite partially decomposes with the precipitation of cementite and the hardness falls. At higher tempering temperatures (about 400 deg. to 500 deg. Cent.) the remaining martensite breaks down with precipitation of the special carbide, so that with suitable size of particle there is a check in the fall of hardness or even an increase in hardness as the tempering temperature rises. The authors do not, however, lose sight of the similar, but more pronounced, effect which can result from the presence of retained austenite. as, for example, in the 12 per cent. chromium steel—Fig. 5. In high-chromium steels containing more than 5 per cent. chromium, quenched from a high temperature, there is a retention of austenite which, on tempering at temperatures up to 600 deg. Cent., decomposes and confers additional

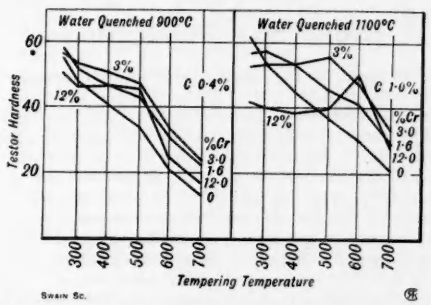

FIG. 5—*Typical Tempering Curves of Chromium Steels.*

hardness on the steel. The austenite retention in a steel with 1 per cent. carbon and 5 per cent. chromium quenched from 1100 deg. Cent. and the increased hardness accompanying its decomposition at 500 deg. to 600 deg. Cent. are demonstrated by the authors. The almost (but not quite) complete absence of residual austenite in the same steel quenched from 950 deg. Cent., accompanied, nevertheless, by a slight increase in hardness on raising the tempering temperature from 400 deg. to 500 deg. Cent. is also shown.

The paper thus contains interesting experimental data on the behaviour on hardening and tempering of chromium steels, and forms a useful contribution to the discussion of their constitution. Westgren* has

† *Archiv Eisenhüttenwesen,* 1932–33, 6, 24.

* *Jernkontorets Annaler,* 1935 (part 6), 119, 231-240.

since published a complete re-examination of the X-ray data, and concludes that the trigonal carbide present in high-carbon ferro-chromium (and continuing, with isomorphous replacement of chromium by iron, down to the low-carbon-chromium regions indicated in the diagrams) is without doubt represented by the formula Cr_7C_3. Incidentally he finds that the trigonal manganese carbide present in ferro-manganese with high carbon content gives such closely similar diffraction patterns that its structure must be the same and its formula Mn_7C_3. The assumption of the authors as to the constitution of the carbide is thus, as Westgren remarks, "happily confirmed," but one other important point, viz., the solid-solubility relationship of this carbide with the α-chromium-iron solid solution is, to a large degree, conjectural. The authors admit that in low-chromium steels which are free from the special carbide there is some degree of delay in the decomposition of martensite, or in the coalescence of the carbide so formed, because of the chromium present. On the other hand, they agree that in steels of high-chromium content there is retention of austenite on quenching. Retained austenite has, in fact, been found by Mathews in hypereutectoid steels with only 2 per cent. of chromium. Thus the range of steels whose behaviour is not accounted for, except by precipitation-hardening, is restricted; and in these instances there is no clear demonstration of increase of hardness on tempering in the proved absence of retained austenite. Until there is a closer co-ordination of the results of magnetic tests and hardness measurements, it must remain a little doubtful whether any precipitation-hardening effect, specially associated with $(CrFe)_7C_3$, or similar carbide existing only in steels with about 3 per cent. of chromium or more, has actually been shown to occur.

Books and Publications.

Introduction to the Study of Physical Metallurgy. By W. ROSENHAIN. Third edition, revised and partly rewritten by J. L. HAUGHTON. 1935. Pp. xvi+368. London: Constable and Co. 20s.

THE publication in 1914 of the first edition of this work was something of an event in metallurgy, as no other book covering quite the same ground had then appeared. In fact, the subject matter was brought to a focus under the new designation, Physical Metallurgy, introduced by Dr. Rosenhain himself. Many have felt that the term hardly connotes all that it has been made to include, and discussion has taken place in these pages (THE METALLURGIST, Vol. VII, 1931), in which alternatives such as Metalphysics, Metallics, and Metalosophy, have been put forward. Fortunately, Dr. Haughton, to whom we are indebted for this new edition, has done nothing to perpetuate these suggestions, though it may be suspected that his own views lean towards a more restricted definition of Physical Metallurgy than that of Dr. Rosenhain.

The original edition was divided into two parts:—(1) The Structure and Constitution of Metals and Alloys, and (2) the Properties of Metals as related to their Structure and Constitution; and although these headings have disappeared, the same division of subject matter remains, and the same clear and attractive style is retained. In the first part of the book three of the original chapters (dealing with the thermal study of metals and alloys, the constitutional diagram—now with some justification promoted to the title of "equilibrium" diagram—physical properties of alloys and typical alloy systems) have been completely rewritten and extended by half their original length. Into this extension much contained in Dr. Rosenhain's later publications has been incorporated, as well as an account of some of the valuable contributions to the technique of metallurgical research for which Dr. Haughton himself has been responsible. Thus, a new form of gradient furnace is described, examples are given of the use of electrical resistivity measurements at different temperatures in the investigation of transformations of alloys in the solid state, and a clear introduction to the study of ternary alloys is provided by the aid of vertical and horizontal sections through the copper-aluminium-zinc and aluminium-magnesium-silicon systems. A section on X-ray analysis, prepared with the help of Mr. G. D. Preston, has also been inserted.

The second part of the book has not been dealt with in the same way. Short accounts are inserted of some subjects which have become important since the date of the last edition—subjects such as inverse segregation, "solution" and "precipitation" treatment of non-ferrous alloys, treatment of cold-worked materials for the relief of internal stress, &c.—but apart from this, only brief references are made to modern work on the subject-matter of the old edition. Hence the impression given of the present position of what may be called the engineering side of Physical Metallurgy is not so complete and well balanced as that conveyed by the first part of the book. The atmosphere of the discussion of some aspects of mechanical testing, for example, is rather remote from that of the Zürich Congress of the International Association for Testing Materials, to the success of which Dr. Rosenhain devoted so much time and labour; and Dr. Rosenhain's post-war publications are not so effectively used as in Part I.

Dr. Haughton anticipates that objections are likely to be made to his retention of the original account of the "Amorphous Theory." Apart from a brief warning of the conflict of opinion on the subject, he has left this chapter substantially unaltered, saying in explanation: "I felt convinced that such alteration would not have been approved of by Dr. Rosenhain himself, as he said to me, when we were discussing the place the amorphous theory should occupy in the book, that he believed there was more evidence in its favour now than ever before."

The great merit of this much-discussed theory lay in the fact that it offered a simple and co-ordinated explanation of a whole series of disconnected facts; and for this reason readers of the book should be grateful to Dr. Haughton for preserving it, instead of giving them what at the moment would be the only possible alternative, viz., a set of *ad hoc* theories involving separate hypotheses and assumptions, often derived from the same fundamental conception, and no better supported by experimental evidence. Readers of Dr. Rosenhain's latest pronouncements on the amorphous theory will have realised that some of the old terms, such as "intercrystalline amorphous cement" no longer retained their conventional and simple meaning. In the light of fuller knowledge of the structure and properties of thin liquid films and of vitreous bodies, they were being elaborated and redefined, though the underlying conception was not weakened. It is perhaps a pity that this is not made clear in the text by incorporating suitable abstracts from such papers as that on "The Plastic Deformation and Fracture of Metals,"

given at the Amsterdam International Congress, as well as from the Royal Society papers on "Neumann Lines" and on "Energy Absorption in Cold-Working."

Whatever the ultimate fate of the Amorphous Theory may be, it is too early yet to lose sight of this great contribution to metallurgical thought and achievement, and the book would have lost in interest and in value if Dr. Haughton had decided against its retention.

Chromium Steels. By R. H. GREAVES, D.Sc. Published by H.M. Stationery Office for the Department of Scientific and Industrial Research. 1935. Pp. 321+vi. 7s. 6d.

ANY review dealing with a metallurgical development over a number of decades must necessarily emphasise the wide scope of the investigations by many workers, which has been necessary to place the development on a sound technical basis, and this work upon chromium steels is an excellent example.

The author states that in connection with researches on chromium steels undertaken in the Research Department, Woolwich, on behalf of the Metallurgy Board of the Department of Scientific and Industrial Research, it was deemed desirable to correlate the data already extant in this field. His work is the result of the decision to publish what is, indeed, a very comprehensive review resulting from his laborious attempt to determine the value of, and to give some order to, the mass of results available. The work has been well done and the volume fills a niche in our metallurgical libraries.

Four excellent monographs on alloys of iron, dealing respectively with molybdenum, silicon, tungsten, and copper, have been recently published in the United States of America; there are also, as Dr. Greaves states, two authoritative works on steels of the stainless type, but hitherto there has been no corresponding publication relating to chromium steels of a lower alloy content. In view of this fact the present volume, which is intended to relate exclusively to plain chromium steels, and deals mainly with those steels whose chromium content is lower than that usually included in the stainless class, comes most opportunely.

Dr. Greaves deals with the early history of the use of chromium in steel metallurgy, not forgetting the use of chromium steel some fifty to sixty years ago in the production of projectiles. The constitution and the mechanical and physical properties of the chromium steels are critically reviewed and the experimental work which has already been done is carefully examined, with the object of clearing the ground for further research. Chapters II, III, and IV, dealing with the constitution of the alloys under consideration, are exhaustive treatments, and other workers can with confidence take full advantage of the author's critical faculty. Considerable space is given to the question of temper brittleness, a subject to which the author and his collaborators have given much attention, to mass effect, to the influence of cold work and to the much-discussed subject of corrosion fatigue. As regards mass effect, the author presents very valuable data which are all the more interesting since in many similar treatises this most important factor is completely ignored. Since, in discussing temper brittleness the complete mechanical properties are given for the stainless steel cited, it is to be regretted that full data were not available for the lower chromium steels. In reviewing the work that has been done on the investigation of mechanical properties, both at high and low temperatures, the author points out the fact that there do not seem to be available any results of tensile tests at high temperatures on low chromium steels, and this is no doubt explained by the rather limited conditions under which such steels are called upon to serve.

Although no work on the quaternary steels, as such, is included, the results of certain hitherto unpublished researches, carried out at the Research Department, Woolwich, are given. They relate to the effect of manganese and silicon on chromium steel, the author regarding these elements not as alloying additions, but as inevitable constituents of all steels. The author has been at some trouble to review the various papers which have been published bearing on the uses of chromium steels, and a brief reference to protective coatings is also included. It is very interesting to be reminded that two investigations had previously covered the compositions of present-day chromium rustless steels without the stainless properties having been discovered, and it is even more interesting to note that Brearley's name, *i.e.*, the inventor of the stainless knife, does not appear in the book.

In an Appendix, Dr. Evans discusses the methods now in use for the chemical analysis of chromium steels, which, as he says, "though apparently simple, bristle with problems." The student would have found this section more valuable if, in addition to his helpful comments on these problems, Dr. Evans had also described in detail the actual methods he employs in analysing these steels.

Full references to the literature will be found at the close of each chapter, and some excellent photomicrographs are included. The book must be considered an excellent review of the work done on chromium steels, and Dr. Greaves is to be congratulated. The volume is well produced, both in form and style, by His Majesty's Stationery Office.

Principles of Phase Diagrams. By J. S. MARSH. McGraw-Hill Book Company. 1935. 18s. Pp. 193 +xv.

THIS is a fascinating book, though it cannot be claimed to be easy reading—but then it is not possible to imagine that any book which dealt at all thoroughly with the equilibrium of heterogeneous substances could be classified as light reading. The writing of the book was started when it became clear to the producers of the Alloys of Iron Monographs that the ternary diagrams included in the monographs "would be largely indecipherable unless a key were provided," and the present volume is that key. Whether it is simple enough to unlock to the average reader of the monographs the vast amount of information contained in the diagrams may be open to question; indeed, it is probable that it is not intended to do so, but there can be no doubt that it will be found of the greatest value, not only to the younger metallurgists and students mentioned in the foreword, but to many an older worker in the field of metallic equilibrium who has been prevented by lack of time, training, or mathematical qualification to study Gibbs, Roozeboom, or Schreinemakers.

Rather more than one-third of the book deals with fundamentals, and this section will be found the most difficult, and perhaps the most valuable. It is not made any easier by its condensation, but that is unavoidable since the book had to be kept to a moderate length. A considerably shorter section then deals with singular and binary systems. One or two points call for comment here. It is empha-

sised that the eutectic line is not a phase boundary. While this is, of course, true, it is part of a boundary between two phase fields, and it might have been well to point this out. Further, is it correct to say (top of page 88) " that *o* approaches *b* as the transformation temperature of B becomes lower " ? Even if it is, should not some proof have been given ? And is Fig. 29 correct ? The phase field $\beta_2+\gamma$ is shown as a single line. Surely it must have finite width ? The reviewer is quite prepared to admit that he may be wrong in these criticisms, but——

At the end of this chapter the author introduces a completely new nomenclature for the various lines on the diagram, which, he points out, is not very necessary in binary systems, but is a great convenience in systems of higher order. In particular, the term " ternary tritectic line " is a great improvement on the inaccurate " depressed binary eutectic line " or the indefinite " binary complex line." Some of the terms, while logically desirable, are probably practically unnecessary. It seems unlikely, for example, that the simple " ternary eutectic point " will be abandoned for " ternary *d*-tetratectic point."

The remainder of the book deals with ternary systems and with a few practical examples. The case which the author discusses most fully as a practical example is the iron-carbon-silicon system. This is perhaps a little unfortunate, as he starts off with the doubtful assumption that the iron-carbide system is the stable one at all temperatures, and then deduces from this and the iron-silicon diagram a ternary system in which the graphite phase is completely ignored. It is well known that silicon in cast iron causes a large amount of the carbon present to separate as graphite. This, however, is one of a very few minor blemishes in a most excellent book which well repays the effort necessary to read it.

Metallurgy : An Elementary Text-book. By E. L. RHEAD. New, revised, and enlarged edition. Pp xiv+382. London : Longmans, Green and Co. 1935. 10s. 6d.

THIS well-known text-book for students of metallurgy has again been thoroughly revised to bring it into line with modern developments, but its scope and intention have not been altered. It provides within a moderate compass an outline of general metallurgy. After several chapters of an introductory character, extended to cover furnaces, refractory materials and fuels, the metallurgy of iron and steel is dealt with in a comprehensive way. Then follow chapters on the common non-ferrous metals and special sections on alloys, pyrometry, and metallography. There is some evidence of the book's history in the present arrangement of its contents. It is unlikely that the author would have adopted quite the same position for his discussions of alloy steels, pyrometry, and metallography if he had been writing the book afresh, and there are other places, especially in the first chapter on the physical properties of metals, where an infiltration of new matter has interrupted the orderly progress of the original. The same effect is produced by the numerous cross references introduced into the text to link up the new material with the corresponding subject matter of the earlier editions.

The author has wisely retained the descriptions of some processes which, though now obsolete, illustrate the principles underlying their modern successors ; but some relics of the early editions should not have been allowed to survive. For example, the statement (p. 19) that " iron and steel frequently become apparently crystalline and brittle by continued vibration " is a most misleading one to leave without amplification or explanation. The main treatment of " Alloys," on pp 335 to 349, is on the old empirical lines, although the material for a logical presentation of the subject is available in the sections on pyrometry and metallography which follow.

The book is likely to cultivate a definitely practical outlook, without, however, ignoring the scientific principles on which practical advances depend. It must be a satisfaction to the author, who is now less directly concerned with the instruction of students in metallurgy, to know that this book, which has proved to be so valuable in the past, has entered upon a new lease of useful service.

The Book of Stainless Steels. Edited by ERNEST E. THUM. Second edition. 1935. Pp. xii+787. Cleveland, Ohio : The American Society for Metals.

THE first edition of this book was the subject of a long review in THE METALLURGIST (March 2nd, 1934, pp. 110–112), in which the complete and comprehensive character of its contents was commented upon. The appearance of a second edition enlarged by 150 pages after such a brief interval reflects the rapidity of progress in this subject.

The book, it will be remembered, is in the form of separate sections contributed by different authorities, and the additional matter is accounted for by five new sections and by extensions to about two dozen of the others. The new sections deal with 5 per cent. chromium steel castings, with 29 : 9 chromium-nickel steels, the thermo-couple alloys chromel and alumel, with " Illium," a complex copper-chromium-nickel alloy containing molybdenum and tungsten, and with railway rolling stock. The subject matter of the sections which have undergone extension is also significant. Articles dealing with composition, constitution and heat-treatment naturally receive most revision, after these casting and arc welding, sometimes rival methods of fabrication, take a high place, while sections on the uses of stainless steel in petroleum refineries, automobiles, and marine engineering all receive additions.

The section which will probably attract most attention, on account of its fundamental interest and broad application, is the admirable review of the " Constitution of Chromium and Chromium-nickel Steels," by V. N. Krivobok. In dealing with the corrosion problem, F. N. Speller confines himself mainly to a discussion of the " Principles and Practice of Corrosion Testing," as in the first edition, but the article on " Resistance to Scaling " is remodelled on broader lines than in the first edition and re-written by Heindlhofer and Larsen. While the investigatory side of the subject is adequately dealt with in a number of such articles as these, the industrial aspects receive attention under about seventy separate headings. The book, in fact, is a mine of information on all points relating to heat and corrosion-resisting steels, and will maintain its place as a standard work of reference on these subjects.

The Physical Chemistry of Steel Making. By C. H. HERTY, JUN., and ASSOCIATES. Pittsburg, Pa., 1934 : Mining and Metallurgical Advisory Boards. 3 dollars.

THE subject matter of this book is discussed in an article on page 50.